Drilling Large Diameter Holes in Rocks Using Multiple Laser Beams (504)

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ABSTRACT

Studies on drilling petroleum reservoir rocks with lasers show that modern infrared lasers have the capability to spall (thermally fragment), melt and vaporize natural earth materials with the thermal spallation being the most efficient rock removal mechanism. Although laser irradiance as low as 1000 W/cm^2 is sufficient to spall rock, firing the beam on a single spot for too long at that intensity causes rock melting and reduces removal efficiency. Also, it is difficult to visualize an efficient way to create a six or eight inch hole by sending one large beam down hole. Alternatives are either to raster the beam to cover the 20 cm hole area or, using a pattern of many small beams illuminated sequentially or in groups, create a nearly circular work face. This paper will present the testing results of the multiple small beam method. The effect on rock removal efficiency of several parameters, including relaxation time between laser bursts, basic patterns of multiple beams, and beam spot overlapping amounts are determined and presented.

1. INTRODUCTION

Since 1997, a team consisting of participants from Gas Technology Institute (GTI, formerly Gas Research Institute), Colorado School of Mines, Argonne National Laboratory and Parker Geoscience Consulting, LLC, have studied the feasibility of using high power infrared lasers for the purpose of creating oil and gas wells. The requirements for such a system would include the ability to create a hole about 20 cm in diameter or more that penetrates to 6000 meters and beyond below the surface of the earth.

The rocks encountered in oil and gas drilling include shale, a rock type defined more by it's fine grain size than by what minerals constitute the rock; sandstone, made up of grains predominantly 62 microns and larger; and limestone, which is defined as being primarily calcium carbonate. Shale is the rock type most drilled, at 70% of the total. Other rock types, such as granites and marbles, are sometimes drilled, but much less often.

1.1 First Test Series, 1997-2000

The first work on this project, funded by GRI, made use of the high power lasers developed by the military for the "Star Wars Defense Initiative". The U.S. Army HELSTF unit at White Sands, NM, allowed access to the 1.6 megawatt Mid-InfraRed Advanced Chemical Laser (MIRACL), an HF laser operating in continuous wave (CW) mode at 3.4 microns wavelength. The U.S. Air Force facility at Kirtland AFB in Albuquerque, NM sponsored a test series on the 7 kilowatt Chemical Oxygen-Iodine Laser (COIL), also operating at 1.34 microns wavelength, also in CW mode. A third test series was performed on the 150 kilowatt and 50 kilowatt CO_2 lasers at the LMHEL facility at Wright-Patterson AFB in Dayton, OH. These lasers both operated in CW mode at 10.6 microns wavelength.

The tests were qualitative in nature, with no idea at the start of the amount of energy that would be required to break the types of rock that are commonly encountered in the course of oil and gas drilling. The tests resulted in three main conclusions:

1. Modern high power lasers have more than enough power to spall (break), melt and vaporize all rock types.
2. All rock types require roughly the same amount of energy to spall, with as much variability within types as between them.
3. The melt created by application of laser energy has characteristics more like a tough ceramic than a brittle glass.

In order to quantify the energy requirements, a Specific Energy (S.E.) value was defined as the amount of energy required to remove a unit amount of rock (equation 1).

$$S.E. = E/V_{delta} = (P_{av} *t)/(W_{delta}/\rho) \qquad (1)$$

Where E is energy in joules, V_{delta} is the volume of rock removed in cubic centimeters, P_{av} is average power in watts, t is the duration of the shot in seconds, W_{delta} is the change in weight of the rock sample in grams and ρ is the density of the rock in grams per cubic centimeter (cc). The units of S.E. are Joules/ cc. S.E. calculated for the first tests gave values from 10,000 to over 50,000 J/cc (Graves and O'Brien, 1998).

Analysis of the first test series data indicated that a revision of the experiment design would result in a better estimate of the minimum amount of energy required to spall and melt rock. After the MIRACL tests, the test series were standardized by maintaining a single beam diameter, 0.635 cm, and a beam duration of 5-8 seconds, with the

goal being to penetrate the samples, which were almost all 5.1 cm thick. The resulting small, relatively deep holes exhibited secondary effects, such as ubiquitous melt and particles remelting due to inefficient purging that absorbed beam energy and reduced penetration rates.

1.2 Second Test Series, 2000-2001

The next test series, funded by the Department of Energy (DOE) through a cooperative work agreement, had as its goals to 1) determine the "absolute" S.E. for sandstone, shale and limestone and 2) test the effects of using lasers in pulsed mode in addition to CW mode. The tests were performed on the 1.6 kW Nd:YAG laser (1.06 microns wavelength) and the 6 kW CO_2 laser (10.6 microns wavelength at the Laser Applications Facility, Argonne National Laboratory.

As discussed above, it was decided that future test design had to be modified to minimize the secondary effects. The amount of material removed by each laser shot had to be enough to measure, but the hole would be kept wider than it was deep to allow efficient purging. The results of the 2001 test series were very encouraging. The S.E. values for all rock types dropped (**Table 1**), with shale decreasing the most, even when the lased rock entered the melting zone. However, with the onset of melting, the S.E. values again increased, illustrating the need to prevent melting for efficient cutting (Gahan, et al., 2001, Xu, et al., 2001).

Table 1. Comparison of early, small hole tests (1998-2000) with shallow, wide hole tests (2001).				
	1998-2000 Test Series		**2001 Test Series**	
Lithology	**S.E. Values**	**Standard Deviation**	**S.E. Values**	**Standard Deviations**
Granite	76,000	63,000		
Limestone	73,000	30,000	23,230	6,924
Salt	13,000	9,000		
Sandstone	128,000	78,000	23,103	14,533
Shale	101,000	68,000	2,987	1,563

1.3 Samples and Sample Preparation

Rock samples used in the test series for this project have predominantly been cores that the oil and gas industry retrieved from wells and used to study the properties of target reservoirs. The cores are stored in repositories such as the U.S. Geological Survey Core Facility in Denver, Colorado, which has been very helpful to the project.

Three rock types were used in the 2002 test series, sandstone, shale and limestone. The sandstone is called Berea gray, a quarry stone widely used for engineering tests such as determining fluid flow parameters, due to its consistent properties from piece to piece. Its physical properties include a bulk density of 2.15 g/cc, which is used in S.E. calculations. Sufficient quantities of shale is much more difficult to find, as it is not a reservoir rock and is not ordinarily cored in oil and gas wells. In order to get enough samples to test, shales from two locations were used in the 2002 test series. They both have bulk densities of 2.38 g/cc. It is also difficult to get limestone samples from well cores that are consistent for any distance in a borehole, so a Paleozoic quarry limestone from the Chicago area was used which has a bulk density of 2.37 g/cc.

The samples, when possible, were disk shaped, about 7.5 cm in diameter and 3-5 cm in thickness. To reduce the number of samples needed, more than one test was often done on a piece of core. Previous experience has made it possible to space the tests to avoid interaction between them.

2. TESTING THE MULTIPLE BEAM CONCEPT

The multi beam concept is difficult to test without a large investment in equipment and time. The concept requires that the beam be switched from spot to spot instantaneously, much like the "chasing" light bulbs in a theater marquee, while illuminating several spots at a time. Depending on the power density needed, there may be over one hundred spot locations in a 20 cm diameter hole.

The equipment available at Argonne is a fiber coupled Nd:YAG laser and a optically positioned CO2 laser, both with 5 axis mechanical stages. The stages can be programmed to accelerate and move very quickly, up to 3000 cm per second, but there is always a finite time before the sample is positioned correctly for the next shot. The samples also are difficult to hold in position if the stage accelerates too quickly. For these reasons, the multiple spot tests experienced increased relaxation time with increased number of spots (**Figure 1**).

2.1 Experiment Design

The multi-beam concept includes creating as close as possible a circular hole, although there is no reason for such except traditional methods using mechanical rotating drill bits create circular holes. It is invisioned that there will be no rotation of any part of the downhole laser assembly. The pattern chosen for this series of tests is hexagonal.

Orthogonal arrangements either left too much area untouched by the laser or too much overlap, wasting laser energy. Octagonal patterns gave better coverage, but require many more spot locations for the circular pattern.

If the laser spots are not overlapped, there is the possibility of spikes and ridges of remnant material forming between the spots. The experiment was designed to test the overlap necessary to keep the work face smooth enough that the laser assembly can be moved downward as the workface moves away. The number of repeated laser bursts was varied for all test configurations to determine the onset of melting with increased exposure.

2.1.1 One and Two Spot Preliminary Tests

The tests started with repeated laser bursts on one spot location, with varying relaxations times between the bursts. The bursts were 0.5 seconds in duration, and the relaxation times were in units of this duration (**Table 2**).
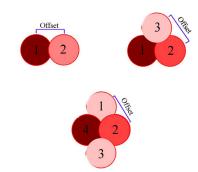

Figure 1. Schematic of spot configuration for the 2002 multi-spot test series. Offsets for 3 & 4 spot tests were fixed at 1.1 cm, while the 2 spot tests were done at 1.0, 1.1 and 1.27 cm spacings.

Table 2. Effect of relaxation time and number of bursts in the single spot repeat test series. S.E. values are averages. All tests are on Nd:YAG laser.

Lithology	Relaxation Time (sec)	Number of Bursts	S.E. (J/cc)	Standard Deviation
Sandstone	0.5	2	6,369	919
		3	6,344	299
		4	7,464	772
		5	9,019	895
		10	27,081	
	1.0	2	6,270	314
		3	9,972	1,479
	1.5	3	7,323	551
		4	10,617	3,054
		5	10,240	2,007
Limestone	0.5	2	313,102	236,387
Shale	0.5	2	3,849	500
		3	4,229	632

The test series continued using two adjacent spot locations, with varying spacings (and therefore, amount of overlap). A minimum relaxation time of 1.5 second between repeating at the same location (0.5 sec to move, 0.5 sec on the other spot and 0.5 sec to move back, **Table 3**) was required for all two spot tests.

2.1.2 Three and Four Spot Tests

A hexagonal pattern consists of a spots at the center and on each of the points of a hexagon, creating a unit cell of seven spots.. The relaxation time that would result from visiting each of these seven spots was considered to be too long to be realistic, so it was decided to break the cell into a series of equilateral triangles and test the effect of one triangle of three spots and two triangles, or four spots (**Figure 1**). Based on the results of the two spot tests, the spacing was set at 1.1 cm between spots, and the relaxation times were the minimums (2.5 seconds for the three spot and 3.5 seconds for the four spot tests). The number of repeats for the three spot tests was varied, up to 30 times at each spot location, while the both of the four spot tests had 10 repeats.

Table 3. Effect of spot spacing and number of bursts on S.E. If S.E. value has associated standard deviation, then S.E. is average of several tests. All samples are Berea gray sandstone.

Spacing (cm)	Number of Bursts Per spot	S.E. (J/cc)	Standard Deviation
1.0	2	7328	
	3	6450	
	4	12242	
	5	11311	
1.10	2	6699	
	3	8638	1082
	4	11441	
	5	17875	2661
	10	54162	
1.27	8	33941	

2.2 Results

The tests had three important positive results.

1. The holes resulting from the multi-spot tests did not show appreciable melting, even though S.E. values increased with increasing numbers of repeats (**Figure 2**).
2. Increasing relaxation time slowed the increase of S.E. with increasing numbers of repeats (**Figure 3**).
3. Ridge development was minor even with no overlap of adjacent

spots (**Figure 4**).

4. The hexagonal pattern seems to work well for the removal of significant amount of material.

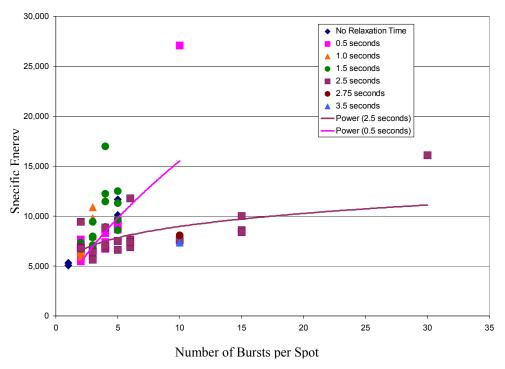There were some negative or ambiguous results as well:

1. The holes narrowed as depth increased, even though the beam was collimated (**Figure 2**).
2. S.E. values were significantly higher than previous "optimization" tests (**Table 4**) and increased with increasing numbers of repeats, which indicate that the holes, though large, were still narrow and deep enough that secondary effects became significant.

3. Discussion

As mentioned in the results above, the S.E. values were significantly higher compared to the "optimal" determinations done with single applications of the laser energy. The meaning of this is not clear at present.

One explanation for the result is related to the configuration of the laser systems being used. The limitations of the equipment are such that the tests are still not what would be expected in an industrial application. The purge system as presently configured angles the flow of gas into the center of the hole from two tubes next to the laser head. This serves to trap particles in the beam as well as blowing them away from the rock. The importance of the purge system can be seen where the tubes are at different angles or there is only one tube blowing at an angle to the beam. In those situations, the hole becomes

Figure 2. Three spot test showing depth of hole with little apparent melt. The spot to the right may have melt present, which may be why it remained shallow compared to other spots. Spot spacing was 1.1 cm, 30 bursts per spot, 2.5 seconds relaxation time. S.E. = 16,079 J/cc.

Figure 3. Chart showing effect of relaxation time on S.E. trends with increasing numbers of bursts per spot. Trend lines using a power equation for 0.5 second and 2.5 second relaxation times have been added. The longer relxation times clearly slow the increase of S.E. with increased exposure to the laser energy.

Figure 4. The amount of overlap determined by changing the distance between spot centers did not affect the ridge development or lack thereof. Tests 1-3 were at 1.1 cm spacing, or 6% overlap, while test 4 is at 1.27 cm spacing, with 0% overlap. Test 1 was 2 bursts per spot, test 2 was 3 and test 3 & 4 were 4 bursts per spot.

Table 4. Effect of number of bursts on S.E., compared to "optimized" values from 2000 test series. Four spot tests used faster acceleration for one value, so relaxation time was 2.75 seconds, and the other was 3.5 seconds.

Lithology	Number of Spots	Number of Bursts per Spot	S.E. (J/cc)	Standard Deviation
Sandstone	Optimized		7868	
	3	2	7486	1279
		3	6030	569
		4	7562	1138
		5	7070	614
		6	8434	2245
		10	7527	
		15	8997	861
		30	16079	
	4	10	8097	(2.75 sec)
		10	7357	(3.5 sec)
Shale	Optimized		518	
	3	2	5549	
		3	4248	
		4	5070	
		6	6374	1694
		10	5533	
		15	10833	1318

asymmetrical, showing that the gas is helping the action of the beam to spall the rock.

Another probable explanation is that, with increasing numbers of repeats, the hole becomes deep enough to allow the secondary effects discussed in the Introduction to become significant. As the hole is opened up by the addition spot locations, the S.E. values may be reduced to an acceptable level for efficient hole creation.

4. Conclusions

The research team is encouraged by the results of the 2002 test series. The combination of several small illuminated spots will be able to create a larger hole. The heat is dissipated quickly enough to prevent melting if the spot is allowed to "rest" between illuminations.

The 2002 test series was very important to the effort to develop a laser drilling system.

1. The tests show that a large hole can be created without the need for moving parts in the bottomhole assembly, such as a rastering or rotating system.
2. The application of a significant amount of laser energy to a small rock sample without causing the onset of melting is very important. Avoidance of melting is essential to efficient rock spalling.
3. The concept of the transport downhole of laser energy by means of fiber optics or other waveguide materials is supported by the low power requirements at each of the many spots to create a large hole in the subsurface.
4. The power requirements are within the tested capabilities of current fiber optics to significant depths, while technology in the research phase, such as hollow core fibers, will allow the use of the laser drilling to depths that the industry is currently capable using mechanical methods.

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